

The role of pre-existing discontinuities in the development of extensional faults: an analog modeling perspective

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Abstract

Several mountainous regions are currently affected by syn- or post-orogenic active extension. We investigate how a newly-formed normal fault interacts with structures inherited from a previous contractional phase. To this end, we use analog models that adopt an innovative technique for performing a precut that mimics such inherited structures into a clay layer; this clay layer is laid on top of a master fault simulated by two rigid blocks sliding along an inclined plane. We carry out six experiments with variously oriented precuts and compare the results with those obtained in a reference isotropic experiment. All other conditions are identical for all seven realizations. Fault evolution is monitored by taking closely-spaced snapshots analyzed through the Digital Image Correlation method. We find that the upward propagation of the normal fault can be either accelerated or decelerated depending on the presence of a precut and its orientation. Such precuts can also promote or inhibit the formation of bending-moment faults. These interactions between master fault and precut also affect the shape of the fault-related syncline-anticline pair.

Keywords. Extension, Normal fault, Pre-existing fault, Analogue modeling, Accommodation space, Blind fault, Active tectonics

1. Introduction

Long-term geological processes, such as the growth and development of extensional faults from their embryonic stage (blind faults) to a mature stage (basin-bounding faults), cannot be appreciated on a human timescale. Two fundamental options exist to overcome this limitation. One is the analysis of natural faults at different stages of maturity at different locations; the other is the analysis of faults through modeling. In principle, the first strategy should be preferred, but identifying a suite of faults having different age and sharing a similar tectonic framework may turn out to be extremely difficult. The second strategy is easier to pursue but its assumptions and limitations need to be carefully considered. Conceptual evolutionary models predict that in a uniform material faults form through the coalescence of Mode I fractures subsequently reactivated in shear (e.g. Segall and Pollard, 1983; Martel et al., 1988; Pollard and Aydin, 1988; Mandl, 2000; Scholz, 2002; Gudmundsson, 2011). The growth history of a natural extensional fault, however, is often more complex than one might expect from such simple models. Rock variability and the presence of older structures (e.g., pre-existing faults) may play a crucial role, for instance, in affecting the geometry of the fault and its extent. These occurrences are nearly inevitable when extension takes place in mountain belts where syn- or post-orogenic extensional structures develop in complex settings created by the superposition of different rock types separated by thrust faults (Fig. 1). Several major mountain belts are currently undergoing extension, including the Himalayas (Molnar et al., 1993), the Andes (Dalmayrac, and Molnar, 1981), the Basin and Range (Wernicke, 1981; Malavieille, 1993), the Taiwan Orogen (Teng, 1996), the Alps (Selverstone, 1988; Bonini et al., 2010; Maino et al., 2013), the Apennines (Elter et al., 1975; Hyppolite et al., 1994; Tavarnelli et al., 2001; Tavarnelli et al., 2003), and the Pyrenees (Chevrot et al., 2011; Lucan and Ortuño, 2012). The growth of faults in these heterogeneous layered settings has been the object of a number of studies (see van Gent et al., 2010; Roche et al., 2013 and references therein). A few studies have also discussed how faults develop when interacting with pre-existing mechanical weaknesses, such as inherited fault zones or thin weak rock layers (e.g., Williams et al., 1989; Faccenna et al., 1995; Tavarnelli et al., 1996a; Tavarnelli et al., 1996b; Cosgrove and Ameen, 2000; Withjack and Callaway, 2000; Tavarnelli et al., 2001; Tvedt et al., 2013; Di Domenica et al., 2014; Tong et al., 2014). In addition, theoretical and numerical analyses have shown that even thin mechanical weaknesses may deflect, stop, decelerate or accelerate the propagation of new faults (e.g., Cooke and Pollard, 1997; Roering et al., 1997; Mandl, 2000).

57 In this study we investigate how the growth of an extensional fault is affected by the presence of a pre-existing
58 frictional discontinuity located in the rock volume overlying the fault itself. To this end we performed analog
59 modeling through a series of six experiments using a clay layer; in each realization a precut is placed with
60 variable orientation with respect to a master fault, thus simulating simple but different inherited structural
61 settings. The results of these experiments are compared with the state of deformation of a reference isotropic
62 experiment (no precut above the fault). We quantify the strain-rate distribution inside the different experiments
63 and reconstruct the evolution of any fault-related folds at significant steps.
64 Our results indicate that during the evolution of a growing extensional fault any pre-existing discontinuity
65 affects (i) the propagation rate of new faults and their ability to reach the surface, (ii) the development of
66 secondary brittle structures related to fault-propagation folding, and (iii) the shape of the related
67 accommodation space together with the migration of the syncline hinge through time. We claim that these
68 elements can be related to the presence and orientation of pre-existing mechanical discontinuities in natural
69 cases.

70

71 **2. Method and experimental setup**

72 Two analog materials are commonly used to investigate the evolution of extensional structures: dry sand and
73 wet clay. These two materials have different properties and are selected by modelers based on the goal to be
74 pursued (Eisenstadt and Sims, 2005). Dry sand is classically used to analyze broad deformation zones and fault
75 kinematics (e.g. Davis et al., 1983; McClay and Bonora, 2001; Ahmad et al., 2014; Toscani et al., 2014;
76 Philippon et al., 2015), as well as the brittle surface expression of blind faults (e.g. Bonini et al., 2011; Galuppo
77 et al., 2015). Wet clay is especially used in studies devoted to analyzing the development of faults and fractures
78 (e.g. Cloos, 1929; Withjack and Jamison, 1986), and the potential reactivation of pre-existing faults (e.g.
79 Eisenstadt and Sims, 2005; Bonini et al., 2014).

80 In this study we use wet clay to simulate the deformation patterns associated with an extensional, initially
81 blind, master fault (Fig. 2). As regards the clay type, we adopt wet kaolin because it is one of the most used
82 and tested clay types for simulating faulting and folding in brittle crustal rocks (e.g., Withjack et al., 1990;
83 Eisenstadt and Sims, 2005; Miller and Mitra, 2011; Cooke and van der Elst, 2012).

84 The experimental apparatus is composed by two rigid blocks juxtaposed along 45° sloping sides, which
85 represent the plane of the master fault. We adopted a dip of 45° for the master fault because worldwide
86 compilations of normal faults show that this is the most common value in tectonically active regions (Jackson
87 and Withe, 1989; Collettini and Sibson, 2001).

88 Wet clay covers the two rigid blocks and represents rocks located above the master fault (Fig. 2). The footwall
89 block is fixed, whereas the hanging wall block is allowed to slide downward along the sloping side. The
90 displacement of the moving block is controlled by a stepper-motor at a constant velocity of 0.005 mm/s. The
91 clay is wet kaolin with density of 1.65 g/cm^3 , water content of 60% by mass, shear strength in the range 50-
92 120 Pa (Eisenstadt and Sims, 2005; Cooke and van der Elst, 2012), and friction coefficient equal to 0.6. Using
93 well established scaling rules (e.g., Hubbert, 1937) we assume that under these experimental conditions 1 cm
94 in our experiment corresponds to about 1 km in nature. In all the experiments the clay layer is 5 cm-thick, thus
95 representing a 5 km-thick brittle continental crust in nature. Black quartz sand grains are placed on the model
96 side to act as displacement markers by creating a visual contrast with the pale-colored clay, hence allowing the
97 model evolution to be monitored. In addition to mapping brittle structural features such as newly-formed
98 fractures and faults, this technique allows us to identify peculiar features of the displacement field, including
99 the trishear zone (Hardy and Ford, 1997; Allmendinger, 1998), and to obtain a high-resolution quantification
100 of the deformation taking place during the experiments. Fault evolution, displacement field, and strain-rate
101 distribution are investigated through the Digital Image Correlation method (D.I.C.; Pan et al., 2009) by
102 analyzing side photographs taken at every 0.5 mm of displacement on the master fault using the PIVlab
103 software (Garcia, 2011; Thielicke, 2014; Thielicke and Stamhuis, 2014).

104 What makes wet kaolin especially suitable for our purposes is the possibility of precutting the clay layer to
105 introduce thin mechanical discontinuities that simulate pre-existing faults or thin layers of weaker rocks. The
106 precut is $\sim 200 \text{ }\mu\text{m}$ thick and is obtained by sliding an electrified blade into the clay layer before starting the
107 deformation process. This technique has already been applied to reproduce long-lived faults both in strike-slip
108 systems (Cooke et al. 2013) and in extensional regimes (Paul and Mitra, 2013; Bonini et al., 2014).

109 Using this setup we conduct seven experiments named from E1 through E7 (Fig. 2a-h, Table 1). E1 is a
110 mechanically isotropic experiment (i.e. without precut). E2 has a horizontal precut in the middle of the clay
111 layer. E3, E4 and E5 have precuts dipping 10° , 30° , and 45° , respectively, with the same dip direction of the

112 master fault (i.e., synthetic planes). The last two experiments, E6 and E7, have a precut dipping 45° and 30° ,
113 respectively, both with opposite dip direction with respect to the master fault (i.e. antithetic planes).
114 The precut is spatially arranged such that it consistently runs 2.5 cm above the tip of the master fault for all
115 experiments. For simplicity, we show snapshots taken at the end of regular intervals of 0.5 cm of displacement
116 on the master fault. In the following, each interval is denoted as follows: 0.0-0.5 cm, Early Stage; 0.5-1.0 cm,
117 Middle Stage; 1.0-1.5 cm, Late Stage. For each stage we provide a display of fault and fracture traces, a set of
118 displacement vectors, and the strain-rate distribution within the clay layer.

119

120 **3. Experimental results**

121 **3.1. Experiment E1: isotropic**

122 During the Early Stage a newly-formed synthetic fault and a smaller antithetic fault propagate upward from
123 the upper tip of the master fault (Fig. 3a), and the fault-propagation folding produces a gentle monocline. The
124 displacement field indicates a trishear zone located above the tip of the master fault (Fig. 3b), and the strain
125 analysis shows that most of the deformation is related to the upward-propagating synthetic fault (Fig. 3c).

126 In the Middle Stage the first synthetic fault slightly propagates upward (Fig. 3d) and two branches appear on
127 both sides of it. Such faults grow by connecting previously-formed small cracks. At the free surface, the
128 steepening of the monocline produces two downward-propagating faults (bending-moment faults).

129 During the Late Stage upward- and downward-propagating faults connect to each other, thereby forming a
130 continuous fault plane that extends from the tip of the rigid hanging wall block up to the free surface (Fig. 3g),
131 and there it forms a fault free face. Displacement vectors confirm the decoupling between the two sides of the
132 fault in the clay layer, showing no motion of the footwall (Fig. 3h). Overall the strain-rate distribution shows
133 that most of the deformation is concentrated along the main synthetic fault, though a secondary synthetic
134 structure located in its hanging wall displays significant activity (Fig. 3i). The heterogeneous strain-rate
135 distribution along the fault traces suggests that these faults form by linking small cracks.

136 In summary, the isotropic model shows that after about 1.5 cm of displacement imparted to the rigid blocks
137 the fault has propagated enough to reach the free surface. This value is then used as a reference maximum
138 displacement to compare the results obtained from the other experiments at the same step. In case the
139 propagating fault reaches the surface before this reference maximum displacement, the experiment is stopped.

3.2. Experiment E2: horizontal precut

In the Early Stage a newly-formed, synthetic fault propagates upward and intersects the horizontal precut (Fig. 4); a small fracture is located above its upper tip, and a bending-moment fault at the free surface accommodates the development of the monocline (Fig. 4a). Displacement vectors depict a trishear zone whose apical angle is located close to the precut (Fig. 4b), attesting faster upward fault propagation than in E1 (compare with Fig. 3b). The strain-rate distribution shows that most of the deformation is confined below the precut (Fig. 4c). As the experiment proceeds to the Middle Stage the upward-propagating fault crosses the precut and connects with overlying fractures and with a newly-formed downward-propagating fault. This new fault system cuts the entire clay layer, as testified by the absence of displacement in its footwall (Fig. 4d). The experiment is thus stopped at the end of this stage. The fault-related folding at this stage produces bending-moment faults at the free surface. The strain-rate distribution shows that most of the slip falls along fault segments that formed in the Early Stage (Fig. 4e).

3.3. Experiment E3: synthetic, 10° dipping precut

During the Early Stage a new fault forms and propagates upward at a slower rate than that of E2, yet faster than the homologous fault in E1 (Fig. 5a). Unlike the first two experiments, no brittle structures are seen above the precut. The displacement field shows a trishear zone that crosses the precut (Fig. 5b). The vectors within the trishear zone exhibit a larger horizontal component than in E1 and E2. The strain analysis shows only diffuse deformation above the precut (Fig. 5c).

In the Middle Stage the upward-propagating fault reaches the discontinuity and stops (Fig. 5d, 5f); only few secondary fractures form at its tip without significant shearing. Two antithetic faults form in the hanging wall of the master fault and a new bending-moments fault accommodates extension at the free surface. The strain analysis shows that most of the deformation is confined below the precut (Fig. 5f).

In the Late Stage the upper tip of the upward-propagating fault remains in the vicinity of the precut (Fig. 5g). Brittle deformation is accommodated in its footwall by another small fracture located close to the precut and by bending-moment faults. The strain-rate distribution and displacement vectors show that there is no connection between upward- and downward-propagating structures. Therefore, at the final step of this experiment the slip at depth is not transferred all the way to the free surface.

3.4. Experiment E4: synthetic, 30° dipping precut

168 During the Early Stage a new fault forms at tip of the master fault and by propagating upward quickly reaches
169 the precut (Fig. 6a). Both the displacement field and the strain-rate distribution show that the upper part of the
170 precut has been slightly reactivated. The composite structure that includes the newly-formed fault and the
171 reactivated precut inhibits the formation of a trishear zone, leaving the footwall almost undeformed (Figs 6b,
172 6c). In the Middle Stage a new synthetic fault forms in the footwall of the previously formed fault (Fig. 6d)
173 and slip on the precut increases (Figs. 6e, 6f). Small fractures form in the zone where newly-formed faults
174 meet the reactivated section of the precut. These fractures appear to be related to the flexure of the hanging-
175 wall block due to the sliding along the composite structure. In the Late Stage (Fig. 6g) the displacement vectors
176 and the strain-rate distribution show that this composite structure reaches a mature stage and the displacement
177 of the rigid blocks is transferred up to the free surface through the precut (Figs 6h, 6i). A secondary synthetic
178 fault located in the hanging wall of the composite structure propagates a bit farther upward, yet it does not
179 reach the free surface. Unlike previous experiments (E1, E2, E3), no bending-moments faults are formed at
180 the free surface.

181 **3.5. Experiment E5: synthetic, 45° dipping precut**

182 In the Early Stage an upward-propagating fault reaches the precut, forming a composite fault that immediately
183 transfers the displacement all the way to the free surface (Fig. 7). Both the displacement field and strain-rate
184 distribution (Fig 7b, c) show that slip is rather uniformly distributed along the precut. The experiment is then
185 stopped.

186 **3.6. Experiment E6: antithetic, 45° dipping precut**

187 During the Early Stage a new fault develops from the tip of the master fault (Fig. 8); its propagation produces
188 a somehow irregular trishear zone above it (Fig. 8b). The strain-rate distribution shows a partial reactivation
189 of the precut, especially in the section near the newly formed fault (Fig. 8c). In the Middle Stage the upward-
190 propagating fault reaches the precut and stops (Fig. 8d). Meanwhile, small fractures form in the hanging wall
191 of the precut, some due to bending. Near the free surface the horizontal component of displacement dominates,
192 thereby promoting the formation of bending-moment faults that are more evident in this experiment than in all
193 other experiments (Fig. 8e). The strain-rate distribution shows that much of the deformation is localized on the
194 surface faults (Fig. 8f). During the Late Stage (Fig. 8g) the upward-propagating fault splits into two splays and
195 crosses the precut. Bending-moment faults are well-developed and exhibit a sizable vertical displacement; yet

they do not show a direct connection with the upward-propagating faults (Fig. 8h). The strain-rate distribution shows the reactivation of the precut (Fig. 8i).

3.7. Experiment E7: antithetic, 30° dipping precut

In the Early Stage (Fig. 9) the upward-propagating fault is slightly more developed and the displacement field is less irregular than in E6 (Figs 9b, 8b). The strain-rate distribution shows only a modest reactivation along the precut and most of the strain is concentrated along newly-formed faults (Fig. 9c). During the Middle Stage the upward-propagating fault reaches the precut and bending-moment faults start propagating downward from the free surface (Fig. 9d, e). In this stage the strain-rate distribution shows that the precut is not reactivated and part of the deformation focuses along an embryonic antithetic fault (Fig. 9f). In the Late Stage upward- and downward-propagating faults are almost connected (Fig. 9g), as testified by the displacement vectors and by the strain-rate distribution (Figs 9h, 9i). Similarly to E6, also in this experiment bending-moment faults exhibit a considerable vertical offset, but in this case also the newly-formed antithetic fault produces significant offset of the free surface.

4. Discussion

In all experiments with precuts (E2-7), and starting from the very early development stage, the geometry and kinematics of brittle structures, the shape of the related folds, the displacement fields, and the strain-rate distributions differ from those seen following the isotropic experiment (E1). These differences are analyzed in detail in the following sections (see summary of results in Table 1).

4.1. Upward propagation of new faults

The role of mechanical discontinuities on the propagation of fractures and faults represents one of the main problems faced by fracture mechanics and material science (see Gudmundsson, 2011, for a summary); as such, it has been the object of several studies. Numerical models, and particularly those based on boundary elements approaches (e.g., Cooke and Pollard, 1997; Roering et al., 1997; Cooke et al., 2000; d'Alessio and Martel, 2004; Cooke and Madden, 2014), yielded encouraging results for geological applications. Among other workers, Roering et al. (1997) analyzed the influence of horizontal, bedding-plane slip on the propagation of a newly-formed, blind reverse fault, suggesting: 1) an increased tendency of the new fault to propagate upward

223 when the frictional plane is above it, and 2) a reduced tendency for the same new fault to propagate further
224 when its tip reaches the pre-existing plane.

225 Although we investigate how pre-existing discontinuities affect the evolution of a normal fault, our
226 experiments yield results qualitatively similar to those obtained by Roering et al. (1997); we observe different
227 velocities in fault propagation, however, also depending on 1) the location of the upward-propagating fault
228 and 2) the orientation of the pre-existing discontinuities (precuts). The upward propagation rate of our newly-
229 formed faults is not constant over time (Fig. 10a), but it either accelerates or decelerates during all experiments.
230 Below we first recall how these faults grow in the isotropic experiment, then analyze the fault-propagation rate
231 in experiments with differently oriented precut.

232 4.1.1. *The isotropic model*

233 The main fractures that can be visually detected on the side of the clay layer in the Early Stage of the isotropic
234 experiment (E1) formed with an acute angle with the vertical σ_1 (ca. 30°), the characteristic angle of shear
235 fractures (Fig. 3a). Such shear fractures (Mode II) - i.e. the upward-propagating faults - connect to each other
236 through small vertical fractures reminiscent of wing cracks (Mode I). In general, this propagation pattern is
237 similar to that expected from crack models and it has been observed both in laboratory tests on rock samples
238 and in field studies (see Scholz, 2002 for a summary and references on this topic). The profile of upward
239 propagation of these faults reflects this process (Fig. 10a).

240 At the very beginning of the experiment the stress concentration at the buried tip of the master fault (i.e. at the
241 boundary between the rigid blocks) increases and generates small *en echelon* Mode I fractures, resulting in a
242 low fault propagation rate (Fig. 10a). When the small, Mode I fractures connect to one another, and become
243 visually detectable Mode II fractures, the propagation rate increases abruptly and the shear fractures develop
244 up to 1.5 cm from the original location of the tip of the master fault. This process is followed by another phase
245 of Mode I crack formation, and consequently the fault propagation slows down. During the Late Stage the
246 upward-propagating fault connects through Mode I cracks located at its tip with downward-propagating faults,
247 thereby increasing the extent of its upward propagation.

248 In summary, the upward propagation rate of newly-formed faults in the isotropic experiment is not constant;
249 it is very slow during the formation of Mode I cracks, but increases abruptly when the cracks start connecting
250 and forming shear fractures. This produces an asymmetric propagation profile, with a nucleation phase

dominated by the formation of small cracks at the tip of the shear fractures and limited upward propagation, followed by a growing phase where small cracks connect to one another to form larger shear fractures, thus determining faster upward propagation.

4.1.2. *Fault-tip upward propagation below the precut*

At the very beginning of all experiments with precut, the characteristics of the upward propagation of new faults are rather similar to those seen in the isotropic experiment (Fig. 10b). However, significant differences in the upward propagation rates start appearing later on, when the newly-formed, upward-propagating shear fractures extend beyond 1 cm distance from the base of the clay layer. At this point, in experiments where the precut is antithetic to the master fault the upward-propagation rate of newly-formed faults is slightly faster than in the isotropic case (Fig. 10b) but slower than in the experiment where the precut is horizontal. The upward-propagation rate of newly-formed faults becomes increasingly faster for an increase in the dip of the precut in experiments where the precut is synthetic to the master fault. Our results thus confirm that discontinuities located above a fault accelerate its upward propagation rate, but this tendency is controlled by the dip angle and dip direction of the precut. This occurrence is probably related to the stress intensity at the propagating tip of upward-propagating faults; as shown by the strain analysis in the various experiments, which is larger when slip on the discontinuity is larger.

4.1.3. *Fault-tip upward propagation across the precut*

A propagating fracture that meets a discontinuity may stop, be deflected, or penetrate such discontinuity. The works by Hutchinson (1996), Xu et al. (2003), and Wang and Xu (2006) established that the behavior of the propagating fracture strongly depends on the *toughness* of the encountered discontinuity, i.e. on the ability of a material containing a crack to resist fracturing. When the toughness is larger than the total strain energy, the propagating fracture penetrates the discontinuity. Conversely, when the toughness is lower than the total strain energy, the propagating fracture is deflected and joins the discontinuity.

In our experiments we observe that the precut orientation controls the propagation process of newly-formed faults when their tip approaches the precut itself. We also observe that a steeper precut dip angle, which determines an increased shear stress with respect to normal stress, favors slip along the precut. More slip is thus indicative of a relatively lower toughness of the discontinuity, and consequently it is also indicative of a promoted fracture deflection. The deflection of upward-propagating faults is promoted in experiments where

279 the dip of the precut is $> 10^\circ$ (E4, E5, E6, and E7; Fig. 10b). In experiments with antithetic precut, the sense
280 of slip on the precut is opposite to that of the main, upward-propagating faults; hence, deflection is inhibited
281 along such an unfavorably oriented plane, resulting in a delayed upward-propagation of newly-formed faults.

282 **4.1.4. *Fault-tip upward propagation above the precut***

283 In E4 and E5 the newly-formed faults reactivate the precut and quickly reach the free surface. In E2 the upward-
284 propagating fault accelerates after connecting with the horizontal precut. In all other experiments (E3, E6, and
285 E7) the newly-formed faults decelerate their upward propagation as they extend beyond the precut (Fig. 10b).
286 In these experiments, such deceleration is probably related to the slip on the precut that accommodates part of
287 the shear strain.

288 **4.2. Antithetic faults**

289 Another important difference between the isotropic experiment (E1) and the experiments with precut (E2-7)
290 concerns the formation of antithetic faults (Figs. 3-9). In the isotropic case, an antithetic fault evolves
291 throughout the experiment and accommodates the material deformation in the hanging wall of the main
292 synthetic upward-propagating faults (Fig. 3). It nucleated at the bend formed by the master fault on the rigid
293 blocks and the newly-formed upward-propagating fault. The same is seen in E3 (Fig. 5), but in this case the
294 antithetic faults are located at the bends of the synthetic upward-propagating fault and terminate their own
295 propagation against the precut.

296 In E2 the antithetic faults cannot be visually detected (left panels in Fig. 4), though some strain concentrates
297 where an antithetic fault may be expected to form (fig. 4e), i.e. on the hanging wall side of the trishear zone.
298 Such an occurrence can be explained by the smooth trajectory of the synthetic fault, which derives from the
299 faster growth rate and lower hanging wall deformation than those seen in other experiments.

300 In E4 and E5 (Figs. 6, 7) the synthetic precuts have a dip $\geq 30^\circ$ and have been partially (E4) or totally
301 reactivated (E5). The reactivation prevents the formation of new antithetic faults by accommodating most of
302 the hanging wall deformation.

303 In E6, the precut is antithetic with respect to both the master fault and the newly-formed upward-propagating
304 faults. In this case, the partial reactivation of the precut prevents the formation of new antithetic faults (Fig. 8).

305 In E7, the antithetic precut only partially prevents the formation of antithetic structures because its reactivation
306 occurs only in the very early stage of deformation (Fig. 9a). No antithetic faults are formed in later stages

307 (Figs. 9f, 9i), although a strain concentration is seen along an alignment whose attitude and dip are compatible
308 with those of an incipient antithetic fault plane.

309 **4.3. Shallow brittle structures**

310 During all experiments, the movement of the rigid blocks and the development of upward-propagating faults
311 produce folding, that is to say, bending of the free surface: anticlines above the tip of the master fault and
312 synclines over the rigid hanging wall. In most of our experiments we observe faults that form near the free
313 surface and propagate downward, evolving through time and space during the different stages of the
314 experiments, yet they are normally confined at very shallow depth. As already mentioned, these minor faults
315 are related with the bending moment caused by the upward-propagation of the main newly-formed synthetic
316 fault. Shallow downward-propagating structures form in five experiments: E1, E2, E3, E6, and E7. They are
317 located along the anticline axis, i.e. where the tensile stress due to bending is largest. In contrast, downward-
318 propagating faults do not form at all in E4 and E5, likely because slip on the main synthetic fault reaches the
319 free surface during the very early stages of deformation (Fig. 10b), thereby minimizing the bending moment
320 at shallow depth. Hereafter, we adopt the vertical projection to the free surface of the tip of the master fault on
321 the footwall rigid block as a reference for the position of these shallow faults (Fig. 10c); positive distance is
322 toward the footwall.

323 At the free surface of the isotropic experiment (E1) the first structure nucleates near the anticline axis at a
324 distance of 2.0 cm (Figs. 3, and 10c). The second surface fault forms at a shorter distance and links with the
325 upward-propagating fault during the late stage of the experiment.

326 In E2, a shallow brittle structure forms since the Early Stage, likely because the development of the fold related
327 with the upward-propagating fault is faster than in other experiments. This shallow fault is located farther away
328 into the footwall than shallow faults observed in other experiments (Fig. 10c), yet it remains within the trishear
329 zone. In the Middle Stage, other shallow faults quickly form at shorter distance but showing only little offset.

330 In E3 a shallow fault displaces the free surface at 2.5 cm distance in the Middle Stage (Figs. 4, and 10c). During
331 the Late Stage most of the surface deformation concentrates on this fault because of the significant slowdown
332 in the evolution of the upward-propagating but still blind faults, likely as a result of the interaction with the
333 precut. This interaction causes a small change of the monocline shape, and, consequently, the maximum tensile

334 stress is always located in the same portion of the fold. Minor faults located at shorter distance are related to
335 the progression of the - minimal, yet clearly visible - fold.

336 In E6 (Fig. 8) and E7 (Fig. 9), the downward-propagating faults are well developed and offset significantly the
337 free surface. This is due to the reactivation of the precut that tightens the anticline at shallow depth, thereby
338 increasing the tensile stress on the fold extrados.

339 In all experiments, the downward-propagating faults form progressively from the footwall toward the hanging
340 wall, though their initial position and vertical offset are variable (Fig. 10c). In the experiments where the
341 upward-propagating faults reach the surface (E1 and E2) the innermost shallow faults form in the early stages
342 and are then linked to the upward-propagating faults.

343 **4.4. Shape of the free surface and migration of the syncline hinge**

344 The shape of the anticlines and synclines and the position of their hinges control the development of secondary
345 brittle structures. Such direct correlation was illustrated in Section 4.3 where we highlighted how the shape of
346 the anticlines and the migration of their hinge points lead to the formation of secondary shallow faults - i.e. the
347 bending-moment faults - while the master fault remains blind.

348 To analyze the warping of the free surface we construct a formline obtained by connecting the shallowest
349 displacement vectors; this allows us to avoid including unwanted artifacts due to the unevenness of the top of
350 the clay layer. All experiments show a different evolution of the fold shape and of the space-time migration of
351 fold hinges (Fig. 11). To highlight the peculiarities of each experiment, we reconstruct 1) the cumulative and
352 2) the incremental shape changes (Figs. 11a and 11c, respectively) at the same intervals as in the fault analyses.

353 The cumulative profiles provide a way of comparing our experimental results with the bedrock of a
354 hypothetical sedimentary basin, i.e. with the shape of the basin floor. Conversely, since erosion, transport, and
355 deposition processes respond dynamically to the changes of the accommodation space, the incremental profiles
356 provide useful information on the evolution/architecture of a sedimentary infill. Similarly to the analysis of
357 shallow faults (Section 4.3), we adopt the vertical projection to the free surface of the tip of the master fault
358 on the footwall rigid block as a reference for the position of fold axes (Figs. 11b and 11d); in this case, however,
359 positive distance is toward the hanging wall.

360 A comparison of the hanging wall of all experiments shows anticline limbs with different inclinations and a
361 variable degree of openness of the synclines (Fig. 11).

4.4.1. Early Stage (from 0 to 0.5 cm)

In the isotropic experiment (E1) the syncline hinge is at about 2.5 cm (Fig. 11a). In most of the other experiments, the syncline hinge is closer to the tip of the master fault, with the exception of E3 whose syncline hinge is the farthest (Fig. 11a). Such differences are due to the different propagation rates of the upward-propagating faults and/or to the amount of slip taken on by the precut. In E3, for instance, the position of the syncline hinge could be related to the slower development of the upward-propagating fault or to a weak reactivation of the precut or to both conditions. The syncline hinge of E2 is the closest, likely because of the faster growth rate of the upward-propagating fault. Regarding E4, E6, and E7, the syncline hinge stays nearly in the same position even if the fault evolution history and the resulting fold shape are different. Indeed in E4 the reactivation of the synthetic precut produces a very open anticline and syncline, whereas in E6 and E7 slip on the precut tightens the shape of the syncline without shifting its hinge (Figs. 11a, b). In E7 a small syncline also forms far away into the hanging wall in correspondence with the precut cutoff and likely due to the partial reactivation of the precut itself. Notice that in all experiments the subsidence of the syncline hinge is about 0.3 cm (Fig. 11a). In E5 no syncline develops because the early reactivation of the precut quickly transfers slip up to the free surface, hence drastically shortening the bending phase.

4.4.2. Middle Stage (from 0.5 to 1.0 cm)

In the Middle Stage the differences between subsequent experiments increase, though all syncline hinges migrate toward the footwall. In E1, the syncline hinge migrates 0.29 cm vertically and 0.6 cm horizontally (Figs. 11b and 11d). E2, E3, and E4 show a similar trend. Conversely, E6 and E7 display significant lowering without any horizontal shift. This is likely due to the concurrent evolution of fold-related faulting and slip on sections of the precut (Figs. 8, 9). This trend is more evident in E6 because the precut is more favorably oriented for being reactivated (dip=45°). Downward-propagating faults begin to be well developed and offset the free surface. In E3 the anticline is also reshaped by a small graben-like structure. The precut reactivation in E4 increases the size of the hollow located on the hinge zone of the major anticline. In E2 the fast development of the upward-propagating fault produces a sort of box fold (Fig. 11a). The analysis of the surface deformation (Fig. 11c) highlights that this box fold is produced by a rapid migration of the syncline hinge due to the evolution of the upward-propagating fault. Figures 11b and 11d show that E1, E2, and E3 have approximately

389 the same horizontal shift values, but the vertical component in E1 and E3 is less pronounced than that of E2
390 and it is insufficient to produce a significant change in the shape of the syncline.

391 **4.4.3. Late Stage (from 1.0 to 1.5 cm)**

392 In E1 the connection between upward- and downward-propagating faults concludes the blind phase of the
393 system. The synclinal hinge migrates toward the footwall at an almost constant rate (Figs. 11b and 11d). In
394 E3, the evolution of the upward-propagating fault is drastically slowed down by the precut (Fig. 10b). Such
395 interaction enhances the little graben near the anticline hinge. In E4 the reactivation of the precut contrasts the
396 migration of the syncline hinge, resulting in its negligible horizontal shift (Fig. 11d). Figure 11c shows how
397 the slip on this anti-listric (convex up) fault results in a uniform subsidence of the hanging wall. In E6 and E7
398 the horizontal migration of the syncline hinge restarts only after that the downward-propagating faults are well
399 developed and the upward-propagating faults cross the precut.

400 **4.5. Modeling limitations**

401 The geometry and kinematics of faults and folds that develop in an extensional system where variably oriented
402 pre-existing discontinuities are located above a master normal fault can be successfully simulated using analog
403 modeling. Before applying our results to analyze natural systems, however, it is important to consider some
404 intrinsic limitations of our experiments.

405 Our experimental apparatus reproduces a planar, 45°-dipping master fault. In nature, extensional faults may
406 have a listric geometry that induces hanging wall deformation driven by the sliding of rocks on a curved fault
407 surface (e.g. rollover and drag folds), potentially broadening the newly-generated accommodation space
408 (Resor and Pollard, 2012). Friction on the master fault plane and secondary normal- and reverse-drag folds or
409 a combination thereof may also control hanging wall deformation (e.g., Schlische, 1995).

410 Other important limitations regard the frictional properties and the number of precuts within the clay layer.
411 They may strongly affect the evolution of the extensional system, amplifying or reducing phenomena that we
412 observe in our experiments (Roering et al., 1997). The shear strength of the precut also depends on its depth,
413 because the deeper the precut, the higher the normal stress acting on it. Therefore, for any given precut setting,
414 a shallower precut can be reactivated more easily. A better characterization of precuts also improves the
415 possibility of comparing them to natural discontinuities.

416 In nature, the dip of the master fault strongly affects both the associated folds and any secondary brittle
417 structures (Withjack et al., 1990). When the master fault is steeper the associated fold is tighter and determines
418 an early development of bending-moment faults. Conversely, when the master fault dip is gentler, the
419 associated fold is open and the extensional structures – or downward-propagating faults – may not form at all
420 because the curvature radius is larger. Moreover, the normal faults may rotate during the evolution (domino
421 rotation), changing their dip and affecting the shape of the accommodation space.

422 The usage of rigid hanging wall and footwall blocks is yet another simplification. In the case of seismogenic
423 faults, for instance, surface deformation is not only produced by coseismic elastic dislocation but also by
424 postseismic relaxation. This is related with the viscous roots and the viscoelastic properties of the lower crust
425 and upper mantle that may contribute to the surface deformation by increasing the wavelength of the surface
426 displacement (Wang et al., 2006; Bürgmann and Dresen, 2008).

427 **4.6. Natural extensional systems**

428 Several currently active extensional systems are located in continental regions that were affected by
429 contractional processes in earlier tectonic phases. These tectonic systems may exhibit various degrees of
430 structural maturity depending on the age of inception and on the strain rate of the ongoing extension.

431 In a very early stage, the extension of an orogenic belt is mainly, though not exclusively, testified by earthquake
432 focal mechanisms and geodetic strain. For instance, the Pyrenees is a mountain chain where the landscape is
433 still dominated by geomorphic features generated in a contractional setting, but where the analysis of focal
434 mechanisms demonstrates that current deformation is dominantly extensional (Chevrot et al., 2011; Lacan and
435 Ortuño, 2012). Considering the tectonic setting of the region and, specifically, the double vergence of the
436 chain, one could speculate that in the Pyrenees some interactions between older contractional structures and
437 younger extensional faults might be occurring in a framework similar to either E4-5 or E6-7.

438 Such interactions have been extensively documented also in the Apennines, where recent earthquakes shed
439 light on the direct interaction between youthful extensional faults and inherited thrusts that affect both their
440 development and their surface signature. For example, Miocene thrusts appear to control the extent of 40°-
441 dipping normal faults that were responsible for the M_w 6.0 and 5.7 mainshocks of the September 1997,
442 Colfiorito, earthquake sequence (Chiaraluce et al., 2003). In the case of the April 2009, L'Aquila earthquake
443 sequence the first mainshock (6 April, M_w 6.3) was caused by slip on a 40-50°-dipping normal fault; this master

444 fault branches upward at 3-5 km depth where it intersect a Miocene thrust dipping 10° in the same dip direction
 445 as the master fault and creates bending-moment faulting at the ground surface (Bonini et al., 2014). In the
 446 second mainshock (7 April, M_w 5.4), that was caused by another 40-50°-dipping normal fault with an upper
 447 limit at about 5 km depth, just below a 20-30°-dipping Miocene thrust; as a result, it showed no connection
 448 with the normal faults lying above it, especially well imaged by seismic reflection lines (Bigi et al., 2013).
 449 Altogether these examples recalls the early-middle stages of E3 and E4 and, considering cases analyzed by
 450 Valensise and Pantosti (2001), suggest that other large active normal faults in the Apennines may be
 451 developing in a framework similar to any other of our experiments.

452 In summary, although extension is currently the dominating tectonic mechanism both in the Pyrenees and in
 453 the Apennines, the structural architecture of these orogens reflects the activity of the large seismogenic normal
 454 faults only to a very limited extent. Instead, their landscape and their earthquake potential are clearly dominated
 455 by the interaction with inherited contractional structures, which ultimately affect the length, the width and the
 456 top depth of the active normal faults.

457 Another example of such interactions has been documented in the northern part of the Taiwan orogen that is
 458 affected by late Quaternary extension (e.g. Suppe, 1984; Teng, 1996; Hu et al., 2002). An active normal fault
 459 (Shanchiao Fault) located in the Taipei basin shows a ramp-flat-ramp geometry whose deeper ramp (dipping
 460 60°) is an ancient extensional fault inherited from a pre-contractional phase (rifting phase of the Chinese
 461 Continental Margin). Its flat portion (dipping 15°) is a Neogene thrust fault, whereas the shallower ramp is a
 462 late Quaternary - hence newly-formed - normal fault (Chen et al., 2014). It is plausible that Quaternary
 463 extension reactivated the ancient extensional fault at depth, which propagated upward exploiting a segment of
 464 the low-angle inherited thrust and then reached the ground surface forming a new high-angle, normal fault.
 465 This unusual case of Quaternary fault development is reminiscent of the results of E3 and E4, and shows that
 466 also a 60° -dipping extensional fault, i.e. a fault steeper than the master faults in our experiments, may stop its
 467 upward propagation against an inherited low-angle structure.

468 Conversely, in a mature system the extensional faults are expected to be well developed and expressed at the
 469 surface. The Basin and Range Province is a renowned example of such a mature extensional system. However,
 470 also in this region extensional structures overprint older contractional structures (e.g. Wernicke, 1992; Parsons,
 471 1995; Axen, 2007). Studies on major earthquakes of this area (e.g. the M_w 7.3, 1959, Hebgen Lake, Montana,

472 and the M_w 6.9, 1983, Borah Peak, Idaho) demonstrate that the normal faults exposed at the surface are the
473 direct expression of large, planar faults dipping 40° to 70° and extending down to 12-16 km depth (Barrientos
474 et al., 1987; Doser, 1989). Notice, however, that some of these fault planes coincide at depth with pre-existing
475 contractional structures (thrust faults) reactivated as normal faults during the extensional phase (Doser, 1989;
476 West, 1992) in a way very similar to what can be observed in E4 and E5. The existence of youthful faults
477 confined at depth (blind faults) and interacting with inherited thrusts that are unfavorably oriented with respect
478 to the current stress field was described in great detail by West (1989; 1992), testifying that inherited structures
479 may play an active role even in regions that exhibit a hypermature stage of development.
480 In summary, depending on the local configuration or on the degree of structural maturity, the inherited
481 structures may directly affect the evolution of youthful extensional faults. Our experiments may help
482 characterizing the evolutionary stage of these faults and understand the causal relationships between the master
483 fault at depth and other structural and geomorphic features.

484

485 **5. Conclusions**

486 We investigated how pre-existing discontinuities affect the growth of extensional structures connected to the
487 displacement on an initially-blind master normal fault. To this end, we used analog models that take advantage
488 of an innovative technique for performing a precut into a clay (wet kaolin) layer laid on top of a master fault,
489 simulated by the sliding of two rigid blocks. Using this original setup, we carried out six experiments in which
490 the precut has various orientations with respect to the master fault, and compared them to another experiment
491 without any precut (isotropic). All other conditions were identical for all seven experiments.

492 Our results show that the presence of a precut can either accelerate or decelerate the upward propagation of
493 the master fault and exert control on several other factors summarized below and in Table 1;

- 494 • a horizontal precut promotes the tendency to grow of upward-propagating faults;
- 495 • low-angle synthetic precuts (e.g. dip 10°) slow down the propagation of upward-propagating faults,
496 but also promote the formation and evolution of shallow downward-propagating surface faults
497 associated with bending moment;

- high-angle precuts ($\text{dip} > 30^\circ$) are prone to be reactivated and may serve as a preferential way for the master fault to quickly transfer slip up to the free surface. If the dip of the precut is lower than that of the master fault, the new fault system will show an antilistric geometry;
- when the precut is antithetic with respect to the master fault one may expect an increase of the growth of the upward-propagating faults and a reactivation of the precut as antithetic faults;
- the various interactions between the growing master fault and the precut also affect the shape of the fault-related syncline-anticline pair and, in turn, the shape of the resulting accommodation space.

These findings may improve our understanding of how extensional fault systems evolve in presence of structures inherited from previous tectonic phases, such as the normal faults that currently affect older orogenic belts. We also suggest that the analysis of the shape and architecture of fault-related continental basins carried out in the light of our findings may provide useful constraints for reconstructing the actual geometry of the master fault at depth.

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709 **Table 1** – Summary of initial conditions and results of each experiment.

Initial conditions				Results					
Precut	Dip angle	Dip direction	Propagation rate ¹			Antithetic faults created	Shallow brittle structures created	Syncline hinge migration rate ¹	
			Below precut	Across precut	Above precut				
E1	No	---	---	---	---	Yes	Yes	---	
E2	Yes	Horizontal	---	≈	>	>>	No	Yes	≈
E3	Yes	10°	Synthetic	≈	>	<<	Yes	Yes	≈
E4	Yes	30°	Synthetic	≈	R	R	Yes	No	<
E5	Yes	45°	Synthetic	≈	R	R	Yes	No	---
E6	Yes	45°	Antithetic	≈	>	<	Yes	Yes	<
E7	Yes	30°	Antithetic	≈	>	<	Yes	Yes	<<

710 1) Mathematical symbols represent relative values of propagation and syncline hinge migration rates
711 with respect to the isotropic experiment (E1); letter “R” stands for precut reactivation.

712

713 **Figure captions**

714

715 **Figure 1.** Schematic cross section showing the early blind phase of an extensional system where new faults
716 grow up and interact with inherited mechanical discontinuities such as thrust faults.

717 **Figure 2. a)** Plan and side views of the apparatus and initial setup of the isotropic experiment E1. **b-g)** Initial
718 setups for the precut experiments E2-E7 (the precut is shown by a black, thick line on the side of the clay
719 layer).

720 **Figure 3.** Side view of the isotropic experiment E1 after 0.5, 1.0 and 1.5 cm of displacement on the master
721 fault (end of early, middle, and late stages, respectively). The fault traces in the left-hand panels (**a, d, g**) were
722 detected through visual inspection: the red lines marks the newly-formed faults developed in the specified
723 stage; black lines are faults formed during previous stages. Central panels (**b, e, h**) show the displacement field
724 detected using D.I.C. (red arrows) and the boundaries of the trishear zone (dotted lines), when present. Right-
725 hand panels (**c, f, i**) display the strain-rate distribution.

726 **Figure 4.** Side view of E2 (horizontal precut). The dashed lines mark the precut; other symbols as in Fig. 3.

727 **Figure 5.** Side view of E3 (synthetic, 10° dipping precut). The dashed lines mark the precut; other symbols as
728 in Fig. 3.

729 **Figure 6.** Side view of E4 (synthetic, 30° dipping precut). The dashed lines mark the precut; other symbols as
730 in Fig. 3.

731 **Figure 7.** Side view of E5 (synthetic, 45° dipping precut). The dashed lines mark the precut; other symbols as
732 in Fig. 3.

733 **Figure 8.** Side view of E6 (antithetic, 45° dipping precut). The dashed lines mark the precut; other symbols as
734 in Fig. 3.

735 **Figure 9.** Side view of E7 (antithetic, 30° dipping precut). The dashed lines mark the precut; other symbols as
736 in Fig. 3.

737 **Figure 10. a)** Progression of upward propagation of newly-formed fault in the isotropic experiment; the color
738 shaded area marks the various stages of propagation. **b)** Progression of upward propagation of newly-formed
739 faults in all experiments. Point symbols mark the position of the precut. Notice that the lines describing the
740 progression of E4 and E5 become vertical when the newly-formed faults join the pre-existing discontinuity
741 and reactivate it (Discontinuity Reactivated; D.R.). The orange shaded area marks the zone of the clay layer
742 where downward-propagating faults tend to develop. **c)** Position of the surface traces of downward-
743 propagating faults in each experiment. E4 and E5 are not reported because no surficial faults were detected in
744 these experiments.

745 **Figure 11.** Profiles of the cumulative **(a)** and incremental **(c)** surface deformation of all experiments, except
746 for E5, after 0.5, 1.0 and 1,5 cm of total displacement on the master fault, and diagrams of the corresponding
747 cumulative **(b)** and incremental **(d)** migration paths of the synclinal hinges. In all diagrams the point symbols
748 mark the position of synclinal hinges taken as the lowest point on the profiles.

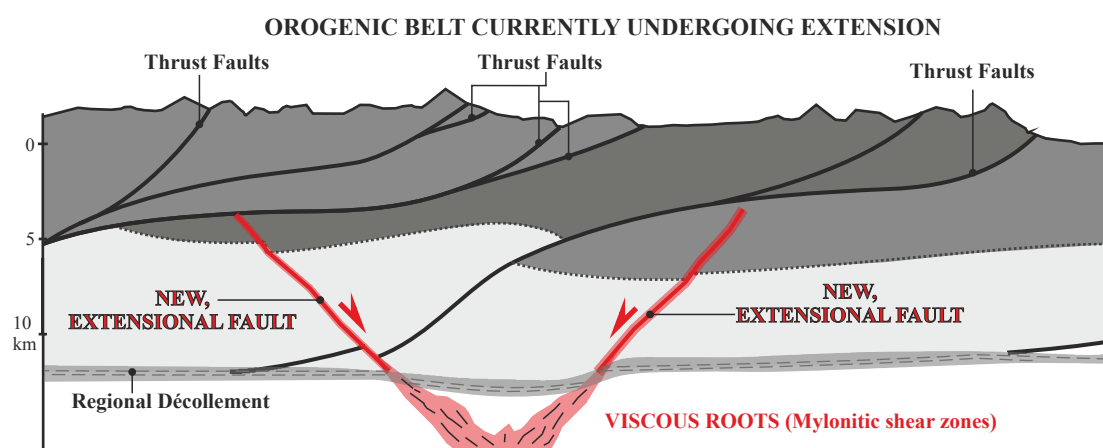


Figure 1

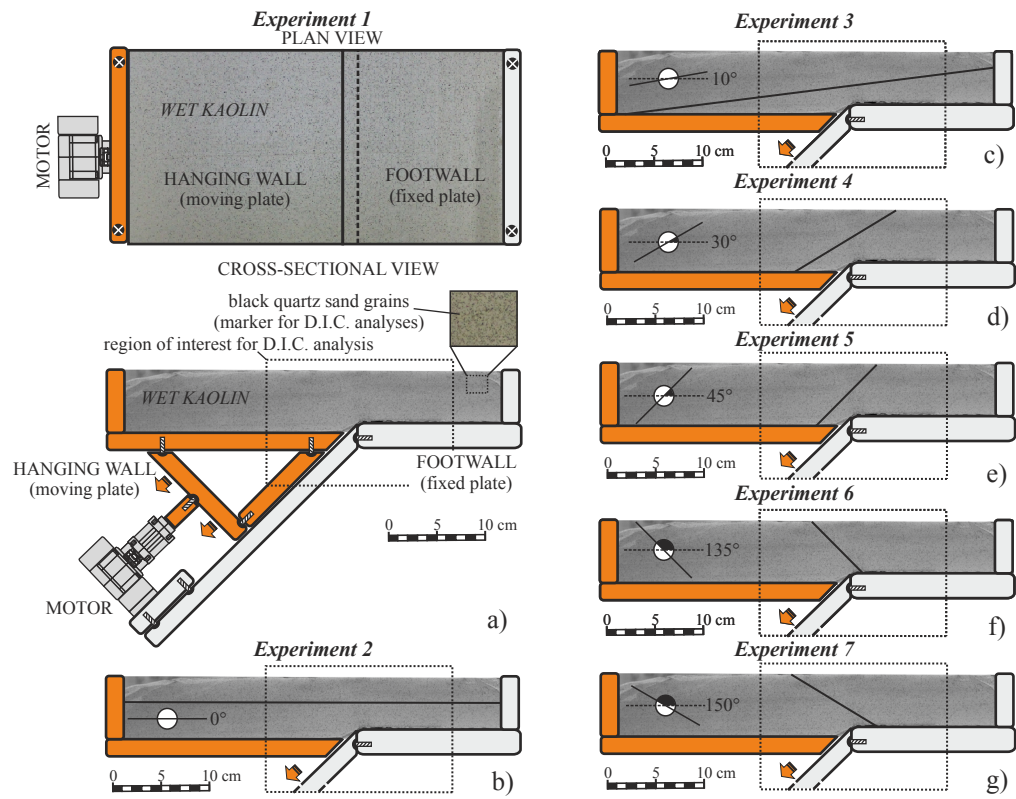


Figure 2

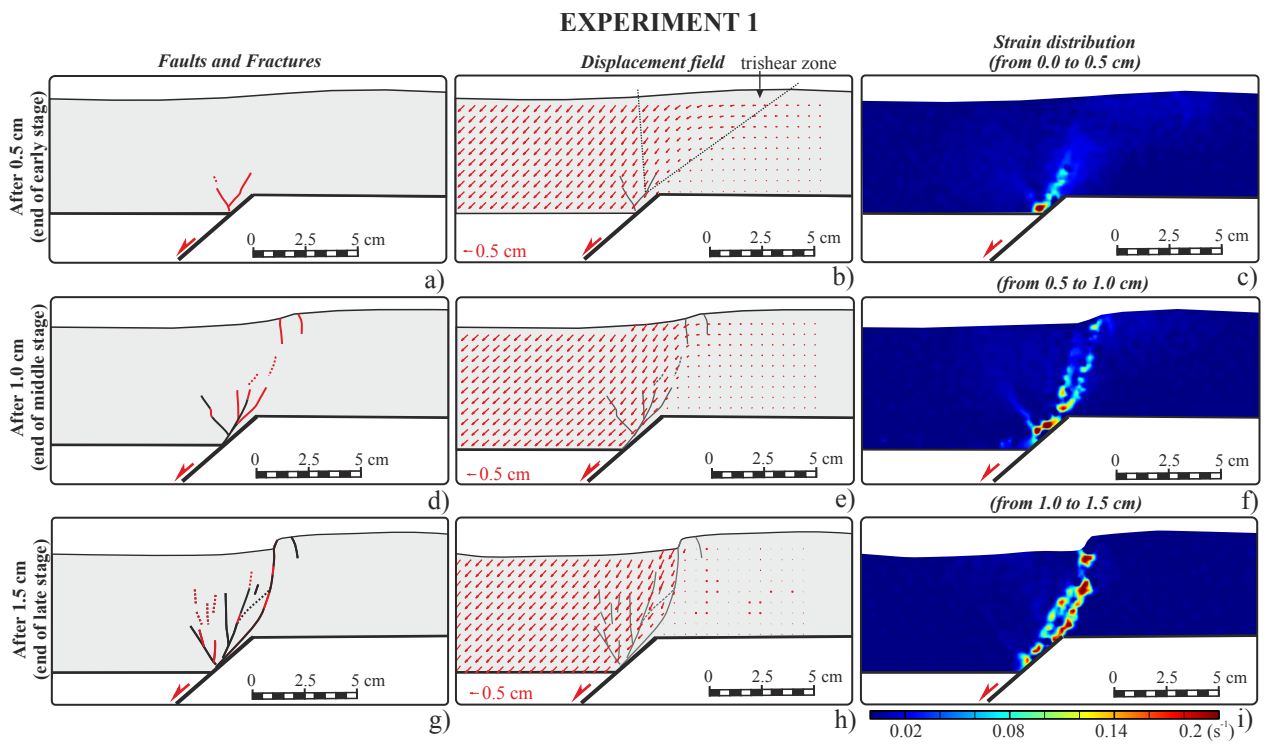


Figure 3

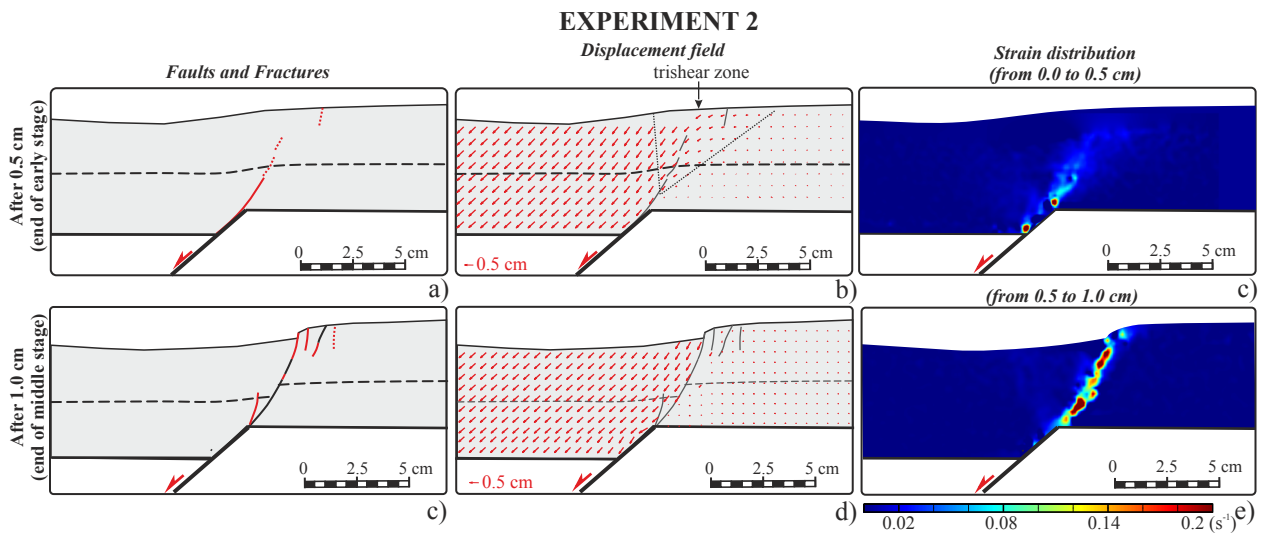


Figure 4

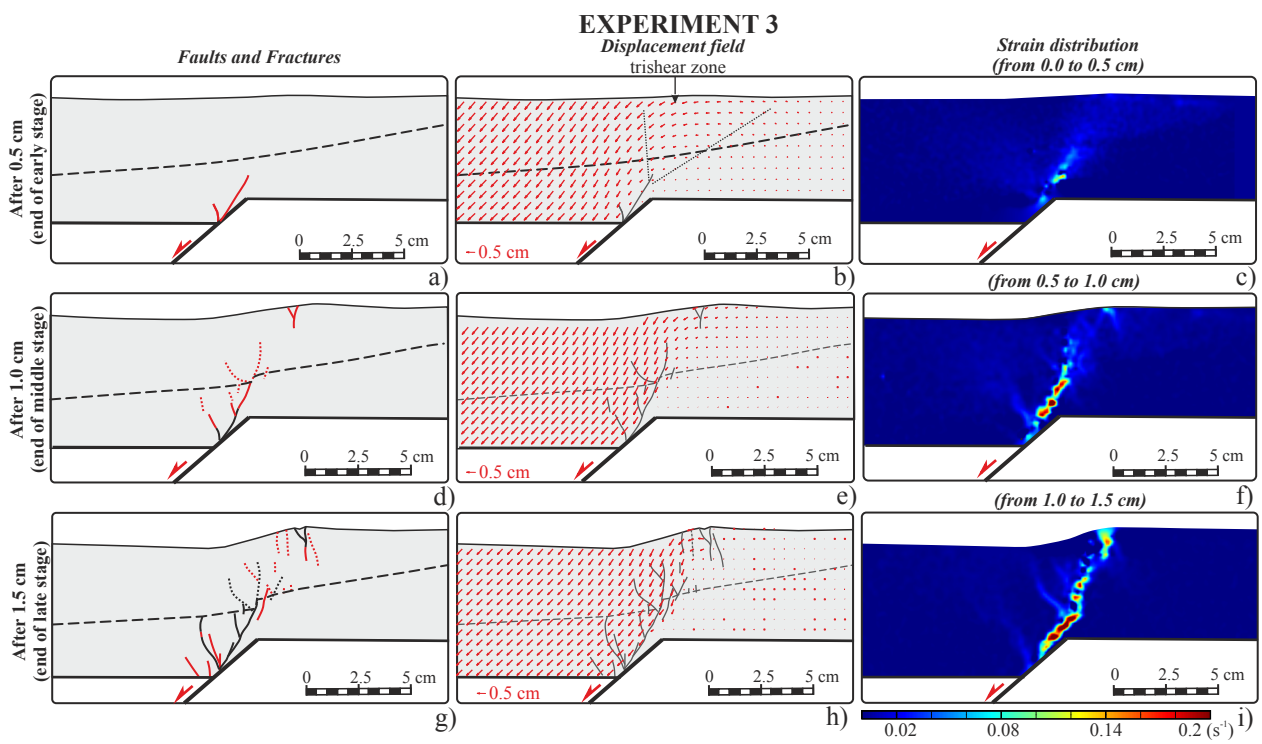


Figure 5

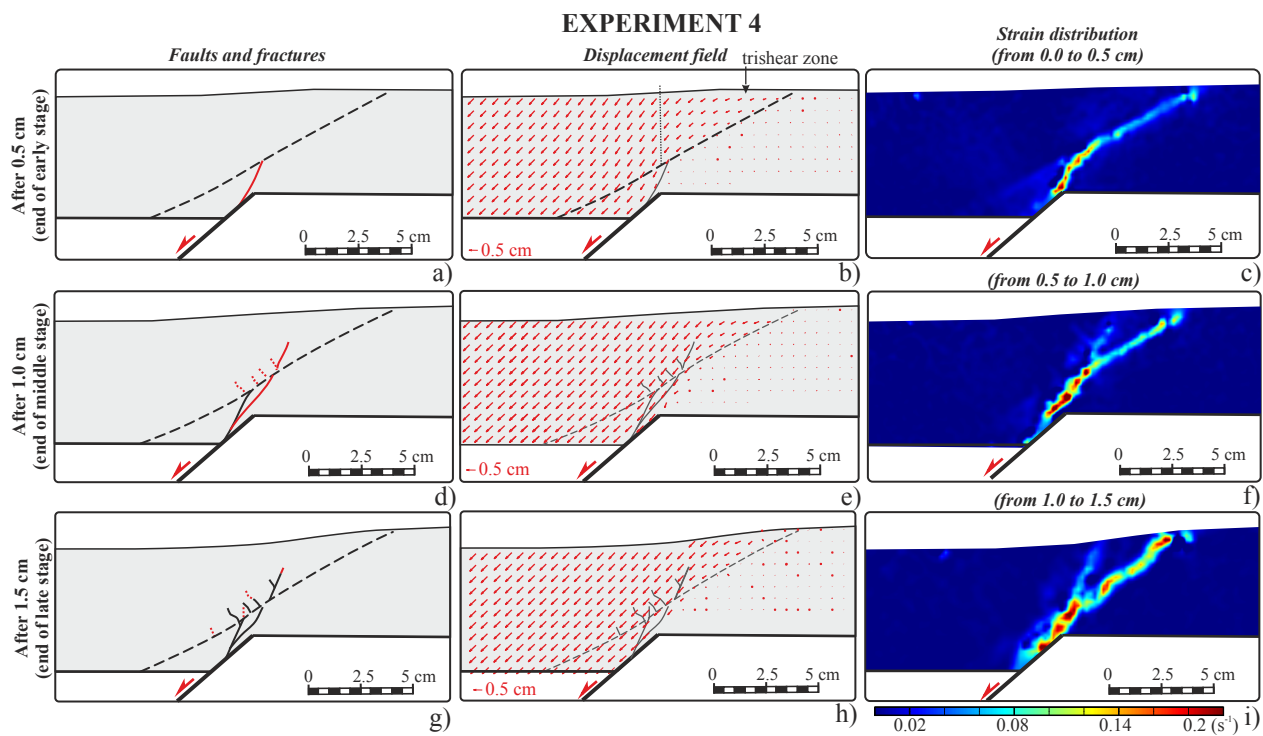


Figure 6

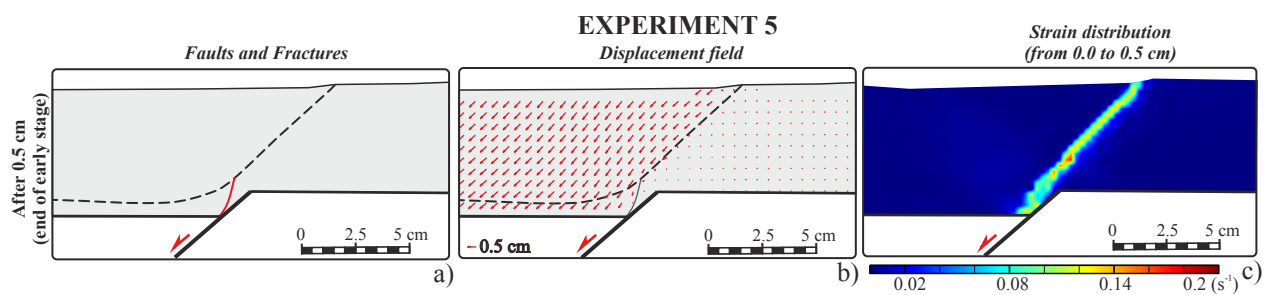


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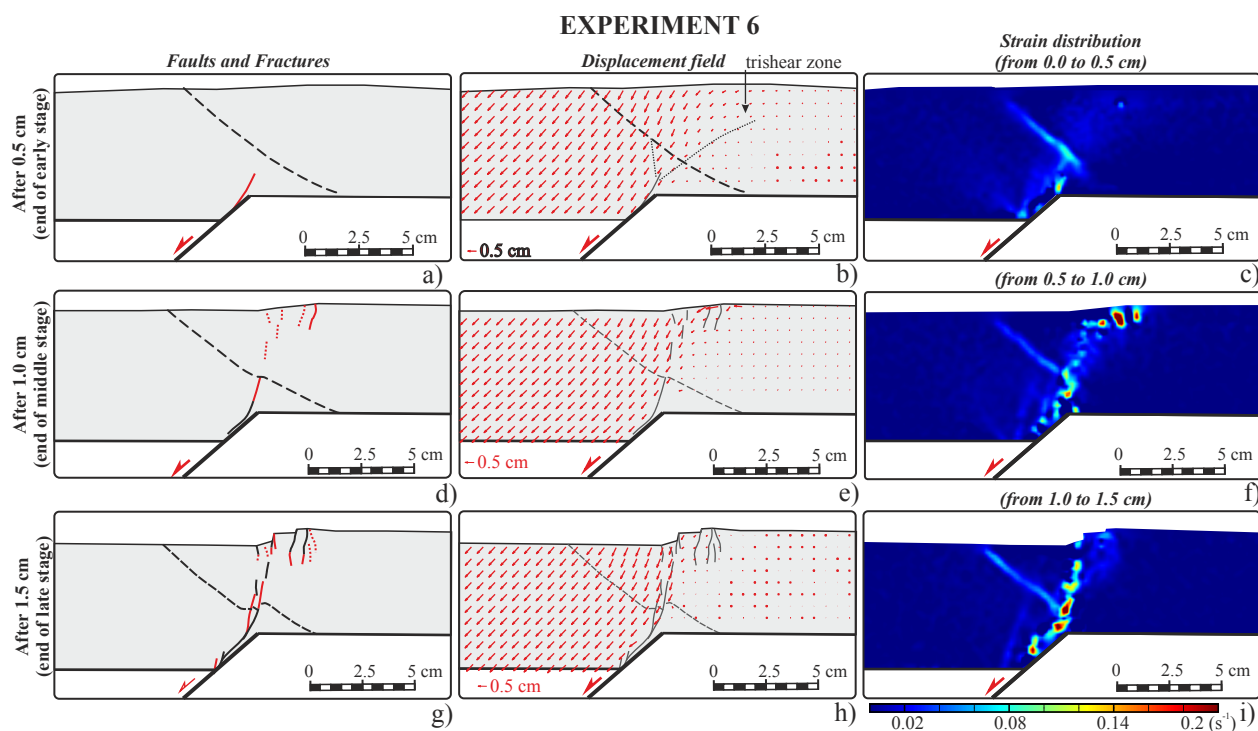


Figure 8

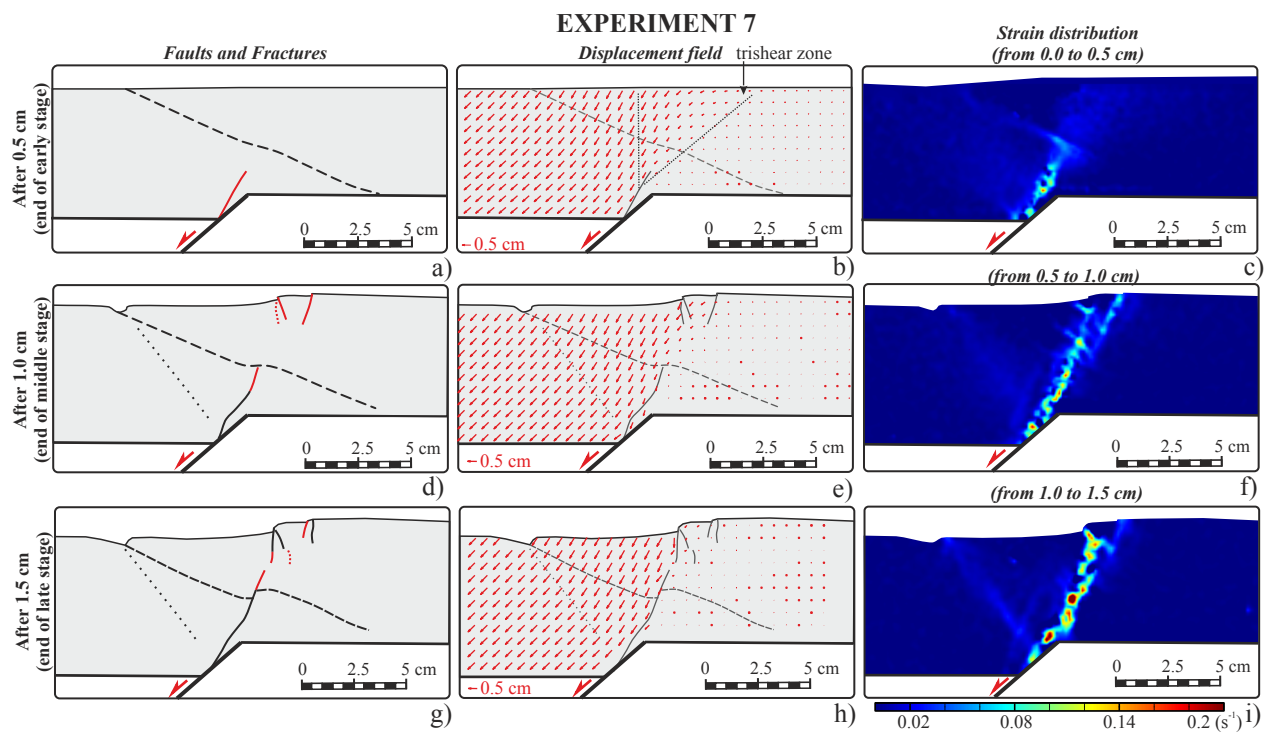
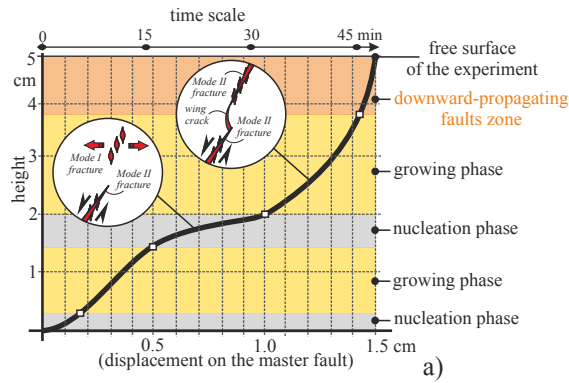
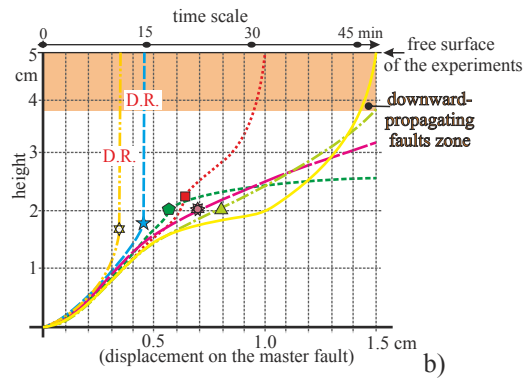


Figure 9

Upward-propagating faults (height above master fault)
Isotropic experiment (E1)



Upward-propagating faults (height above master fault)



Downward-propagating faults (surface traces)

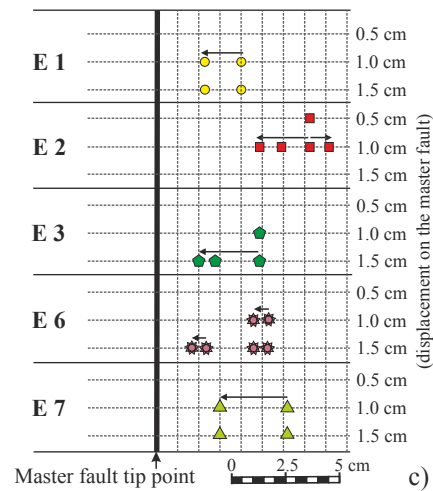


Figure 10

